

First and subsequent return stroke properties of cloud-to-ground lightning

by

S.Namasivayam and Stig Lundquist
Institute of High Voltage Research
A Department at Uppsala University
S-755 92 Uppsala
Sweden

Abstract

Lightning properties obtained by a network of magnetic direction finders and by electric field measurements for distances from 50 to 500 km are compared for three summer thunderstorms in Sweden. The data from direct field recordings indicate 31%, 17% and 26% of negative subsequent return strokes with peak current (as inferred from the peak electric field) higher than the first. Electric fields from first strokes are compared with normalised amplitudes registered by the magnetic direction finding system. The efficiency of detection by the magnetic direction finding system is discussed in terms of the percentage of lightning flashes observed by electric field measurements that are not localised. Statistics of the number of strokes per flash and the interstroke time intervals are presented.

Introduction

In Scandinavia, cloud to ground lightning is monitored by a ground based commercial lightning location and registration system (LL&R) which provides information about the coordinates of the striking point, the amplitude of the first stroke field transition, the total number of strokes in each flash (multiplicity) and the time of occurrence of each flash. In the summer of 1988, the vertical electric field of natural lightning was measured (by one of us, S.N) during several thunderstorms and compared with the data collected by the LL&R system.

Experiment

The electric field sensor was a flat plate antenna oriented parallel to the ground. The instrumentation consists of a transient recorder capable of storing waveforms spaced a millisecond apart with a date and time tag on diskettes [1]. The data consists of time waveforms of 600 μ s duration at a sampling spacing of 1.14 μ s. The decay time constant of the antenna system was chosen to be longer than the duration of the recorded waveforms. A preamplifier at the antenna provided impedance matching and the output of the preamplifier was connected to the transient recorder by a 20m long coaxial cable terminated with the characteristic impedance.

Results and discussion

From the data stored on diskettes, the characteristic signature of the return stroke field transitions can be easily identified. For a return stroke waveform, with a corresponding registration from the LL&R, the distance to the point of strike could be obtained. There were instances when more than one LL&R localisation data matched the time tag of the return stroke waveform within a set selection limit of one second. If this was in the case of flashes with more than one stroke, then a visual check of the waveforms was performed to verify that no

subsequent stroke has been classified as a first stroke. First stroke waveforms are characterised by several subsidiary peaks following the initial rise to peak of the wavefront [2]. Further if two or more multiple stroke flashes were registered within the selection limit then these were not used in the analysis of data since the particular sequence of recorded waveforms could have been from different flashes which would lead to error for e.g. in the estimation of interstroke interval. First strokes whose initial peaks exceeded the full scale voltage range of the transient recorder were excluded from the analysis of amplitude distributions but were included in estimating interstroke intervals. As will be discussed later in this paper, there were also several cases of recorded return stroke waveforms with no matching registration from the LL&R.

Figure 1a, 1b and 1c show the comparison of the registered LL&R network amplitude units to the recorded initial peak electric field in V/m of negative, positive and both negative and positive first strokes together respectively. Approximately 90% correlation coefficient is observed in the cases of positive and both positive and negative first strokes together. For 100 LL&R amplitude units the measured electric field is approximately 3.0 V/m which is in fair agreement with an earlier estimate of 3.6 V/m [3]. Since the spread of data around the line of best fit was larger for negative first strokes, for a selected number of cases, the measured peak electric field was compared to the registered LL&R network amplitude units and to the Uppsala DF station field strength units and the results are shown in figures 1d and 1e respectively. Although a slightly better correlation coefficient is observed in the latter (comparing figure 1d to figure 1e), similar values of DF field strength units are observed for several different measured peak electric fields between 2 and 2.5 V/m. A possible explanation could be that the resolution at the lower end of the voltage range of the DF unit is limited due to the fewer number of bits used to represent the voltage signal in digitised form. This would not contribute to errors in localisation as only the angles from DF stations are utilised to compute the point of strike (except in the case of baseline calculation) but would result in an incorrect estimation of the normalised amplitude units as calculated by the LL&R network. Localisation errors of the LL&R network could however be attributed to the difference in the spread of data between figure 1d and 1e around the line of best fit.

The amplitude distribution (normalised to 100 km) of the electric fields of single stroke flashes is shown in figure 2 and of the first stroke from flashes with multiple strokes in figure 3. The geometric means of the initial peak electric field amplitude distributions for single stroke flashes and for multiple stroke flashes do not show any significant difference and are in good agreement with earlier observations in Sweden [3]. Measurements from Florida have shown a lower geometric mean initial electric field for single stroke flashes than first strokes in multiple stroke flashes [4].

From measurements by Krider et al in Florida [5], we infer that at least 10% of the electric fields from subsequent strokes preceded by dart-stepped leader processes were higher than the first stroke. In Sweden, measurements indicate a significantly larger fraction of subsequent strokes with the highest electric field peak in a multiple stroke flash. For three thunderstorms observed during the periods 7-8th June 1988, 27-30th June 1988 and 15-16th July 1988, from multiple stroke flashes, the percentages of subsequent strokes with electric field peak amplitudes higher than the first stroke were 31%, 17% and 26%. The ratio of the peak amplitude of the

largest stroke in a flash to the peak amplitude of the first stroke in the same flash for the data from 7-8th June 1988, is shown in figure 4. The results show a significant number of subsequent strokes with higher field peaks for flashes with weak first strokes. The return stroke peak current is strongly correlated with initial peak electric field [6]. If this correlation is applied to derive the peak current from the initial peak electric field data then the peak current for a significant number of subsequent strokes are larger than for first return strokes. This can have several practical implications. Assuming the relationship $d_s = 10 I^{0.65}$, where d_s is the striking distance [7] the protection zone e.g. by a lightning conductor over an electrical installation is reduced by a weaker first stroke and a more vulnerable point can be struck. Worse damage could result if followed by a subsequent stroke possibly having larger derivative of current and a larger current. Further, the mean time between failures (MTBF) for the performance of metal varistor oxide (MOV) used as current surge protective devices is strongly dependent on temperature, a critical number of current surges and the time derivative of the current density [8]. If a transient current surge in a powerline either by a direct strike or induced by a nearby strike is suppressed by the MOV device, it would be heated by the energy absorbed. In the event of a subsequent stroke with higher energy, the deterioration effects on the device could be expected to be higher.

Measurements of the current of direct strikes to instrumented towers show, however, that the peak current for first return strokes are significantly larger than for all subsequent strokes [9]. Since the initial peak electric field depends not only on the peak current but the velocity of propagation of the wavefront along the return stroke channel it is possible that a smaller current travelling faster upwards along the channel could still produce higher electric fields. Another explanation could be that the return stroke channel previously traversed by the first stroke has cooled sufficiently to be non conducting some hundred metres close to the ground. Calculations of the time necessary for a previously established return stroke channel of 2.5 cm diameter to cool sufficiently to a temperature for which the channel becomes non-conducting, indicate a value close to 100 milliseconds [10]. If this is the case then a stepped dart leader could establish a spacially separate channel linking the lowest point of the conducting part of the channel to the ground for a subsequent stroke. A return stroke current flowing in a channel some 50-100 metres from the ground level would be sufficient to produce an electric field with risetimes of the initial peak of the order of a few microseconds. A consistent feature observed in many of the subsequent stroke waveforms with larger amplitudes than the first stroke was either the very pronounced pulse characteristics of leader steps or a very disturbed field preceding the abrupt transition to peak (see figure 8b and 9c). If the decrease of the speed of descent when a dart leader transforms into a dart-stepped leader, would lead to an accumulation of the hitherto smooth flow of charge brought down by the dart leader then it is reasonable to expect larger currents if the return stroke neutralises a major portion of this charge. From simultaneous measurements of optical and electric fields in Florida, [11] the peak optical output from a subsequent stroke preceded by dart-stepped leader is less than for the first stroke (figure 4 of their paper) with the electric field of the subsequent stroke higher than the first stroke. Since the peak light intensity is correlated to stroke peak current, the current in the dart-stepped subsequent strokes may be expected to be less than in the first stroke. If a dart-stepped leader forges a spacially separate channel, then the point of strike could be different for the first stroke and the

subsequent stroke and the arguments presented earlier regarding the vulnerability of an electric installation to multiple strikes may not be valid.

Figure 5 depicts the interstroke interval of the subsequent strokes as a histogram and it follows that a large percentage of subsequent strokes with an interstroke interval of more than 100 ms are present. The most probable interval is between 30-90 milliseconds, and the geometric mean inter-stroke interval is 0.89 secs in good agreement with measurements in Florida [12,13].

The amplitude of the large subsidiary peaks as a fraction of the initial peak for first return stroke waveforms have been reported from measurements in Florida [2] and Sri Lanka [14]. From the data given, the mean amplitude ratios of the second subsidiary peak to the initial peak are 0.8 ± 0.1 , 0.7 ± 0.2 (two storms in Florida) and 0.82 ± 0.14 (Sri Lanka). Using the number of observations given, at most 4 of 72, 2 of 36 and 3 of 53 would have the second subsidiary peak larger than the initial peak. However, in Sweden, from the 7-8th June 1988 data, of 379 single return strokes which were localised between 90-200 km, 108 had larger subsidiary peak amplitudes than the initial peak amplitude of the waveforms. Of all first return stroke waveforms analysed, 6% had ratios greater than 1.3 and were not localised by the LL&R probably due to the requirements imposed by the DF electronics that no subsidiary peak can exceed the first peak amplitude by more than 20%. From the 7-8th June 1988 data, for distances of the location of strike between 100 and 300 km, the amplitude of the large subsidiary peaks as a fraction of the initial peak of localised strokes are depicted in figure 6. The highest number of peaks recorded was seven and the separation between the initial peak and subsidiary peaks is summarized in figure 7. Of 420 waveforms 44%, 20% and 12% had the separations between the first and second, second and third, third and fourth subsidiary peaks within 10 μ s from each other but only 4% had all three subsidiary peaks within 10 μ s from each other. These fractions of waveforms represent a higher value than in Florida and lower than the data from Sri Lanka indicate. The small peak following the initial peak reported by [2] was sometimes observed on both first and subsequent strokes. We have not attempted to analyse these due to the limited resolution of the recording instrument. However, the time separations were at least 2-5 μ s from the initial peak. Since the second subsidiary peak in most cases were large it was difficult to discern whether these small peaks were always present. The mean separation of the second subsidiary peak from the initial peak is probably biased towards a lower value due to the presence of the small peaks. A noticeable feature when comparing the waveforms of return strokes localised at more than 100 km (figure 9) with a return stroke within 50 km (figure 8) is the width of the subsidiary peaks are very narrow and more closely spaced for the closer return stroke waveform. The amplitudes of the subsidiary peaks are probably attenuated and their widths are broadened by propagation over finitely conducting ground. If the DF station electronics reject the stroke on the criteria that the amplitude of subsidiary peaks for the closer strokes are more pronounced, then the subsequent stroke may be accepted as a first stroke. In the case of a strong return stroke it is possible that the next DF station would accept the waveform after subjection to propagation. In the case of first strokes with small peak amplitudes probably a lower multiplicity would be registered by the LL&R network.

Typical first and subsequent return stroke waveforms have been recorded by direct field measurements that were not localised by the LL&R network. The waveforms not localised by

the LL&R due to high subsidiary peaks formed only a fraction of the total. Since distance is unknown, we could only guess whether these were strong or weak strokes. We therefore present the data as a percentage of the total data used in this study. Of a total of 1419 consisting of both first and subsequent strokes, 206 first and subsequent return stroke waveforms were not localised giving a detection efficiency of less than 85%. Further for flashes localised within 150 km from the measurement location, a higher number of subsequent strokes were recorded than the multiplicity registered by the LL&R. Therefore the number of return strokes in a flash are calculated using the electric field record for distances upto 150 km and compared to the data for multiplicity given by the LL&R network. From the 7-8th June 1988 data, the average number of return strokes in a flash obtained from electric field records is 2.1 with a standard deviation of 1.4 and from the LL&R network is 2.7 with a standard deviation of 1.9.

In this report we have tried to evaluate the data given by the LL&R network by measured electric fields. The results obtained in this study show that the data obtained using a LL&R network must be interpreted with caution. It may be necessary that in order to obtain better results the selection criteria must be appropriately set to the signature of lightning electromagnetic radiation fields for a particular region.

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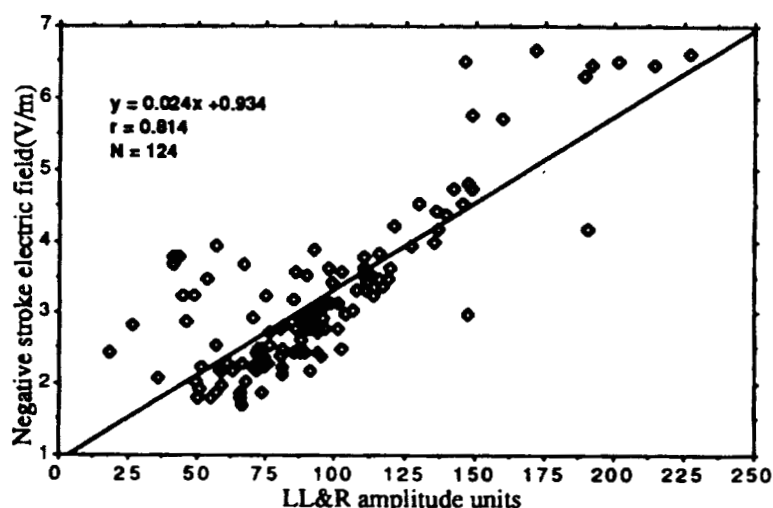


Figure 1a: Measured electric fields and the corresponding LL&R amplitude units

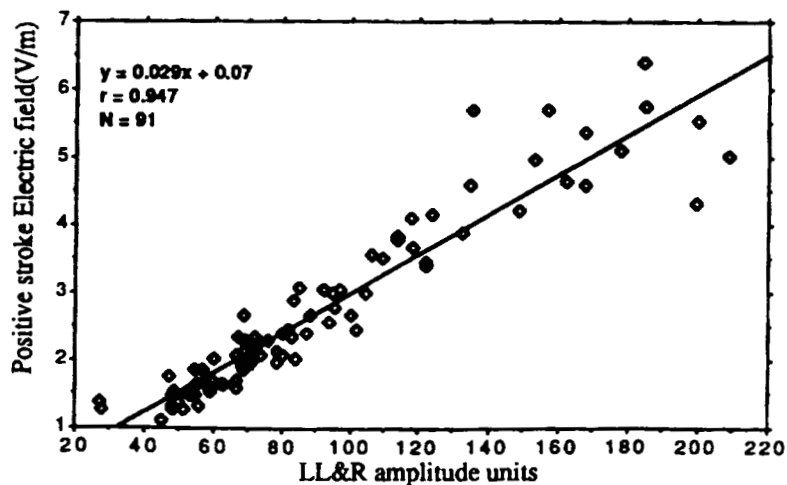


Figure 1b: measured electric fields and the corresponding LL&R amplitude units

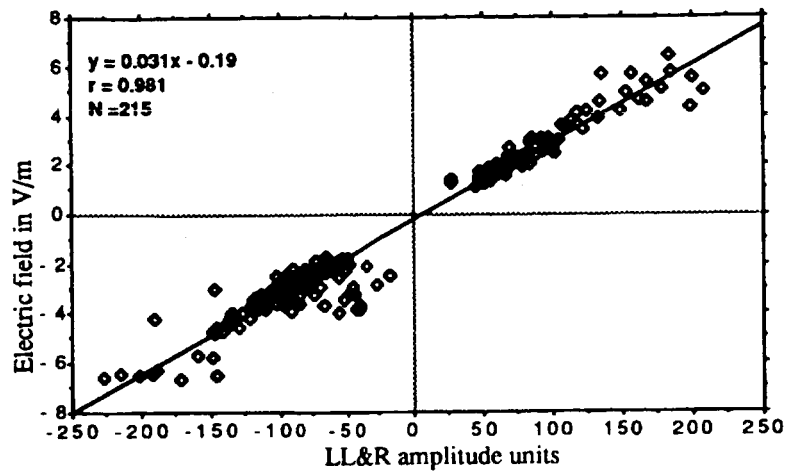


Figure 1c: Measured electric field and corresponding LL&R amplitude units

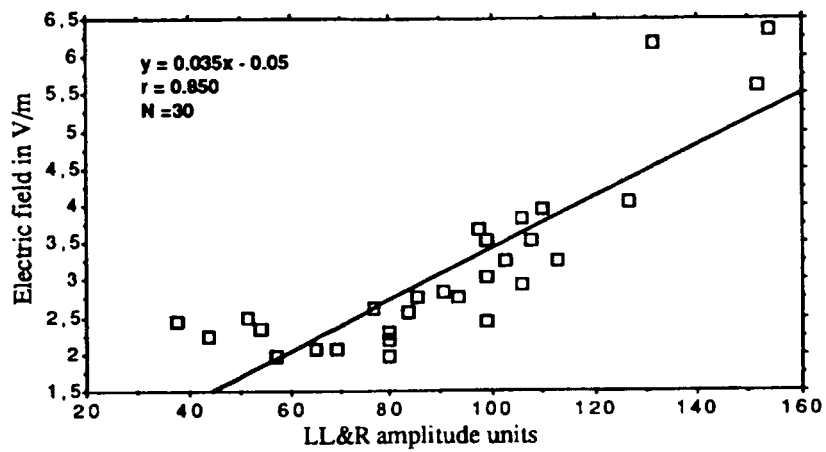


Figure 1d: Measured electric field and corresponding LL&R amplitude units

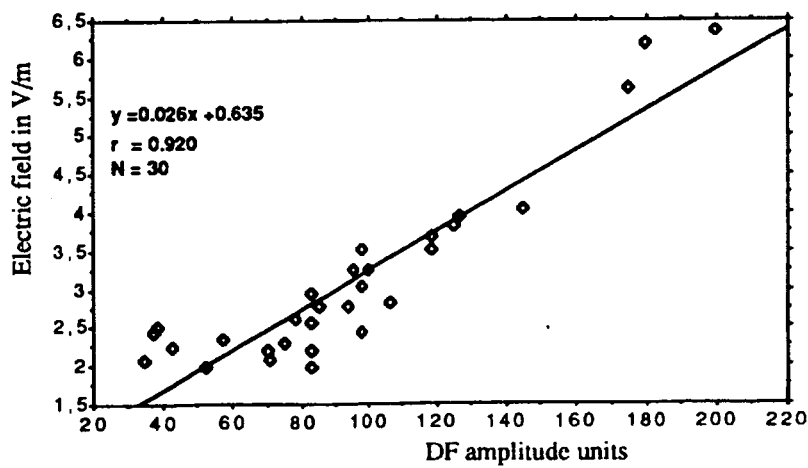


Figure 1e: Measured electric field and corresponding DF amplitude units

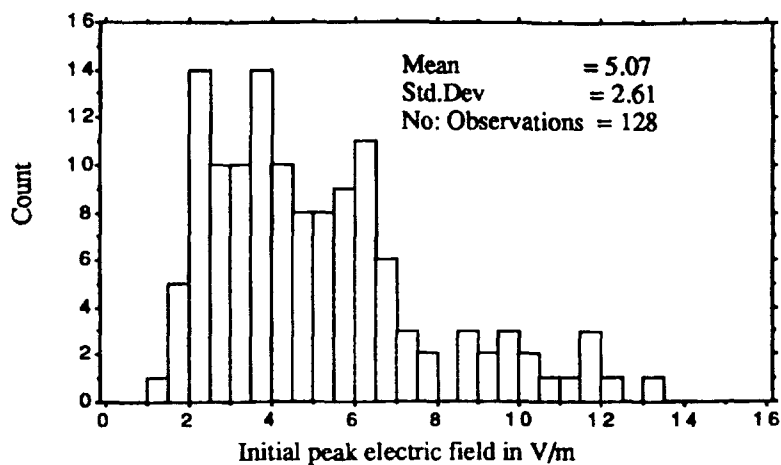


Figure 2: Distribution of normalised (to 100 km) amplitudes of negative single strokes

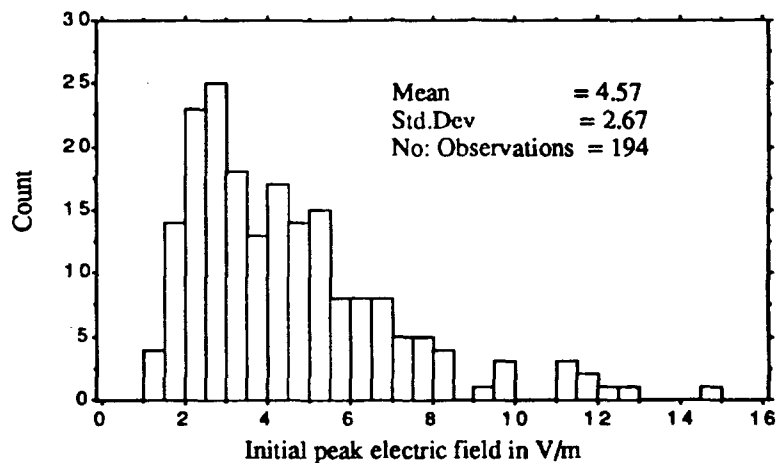


Figure 3: Distribution of normalised (to 100 km) amplitudes of negative first strokes in multiple stroke flashes

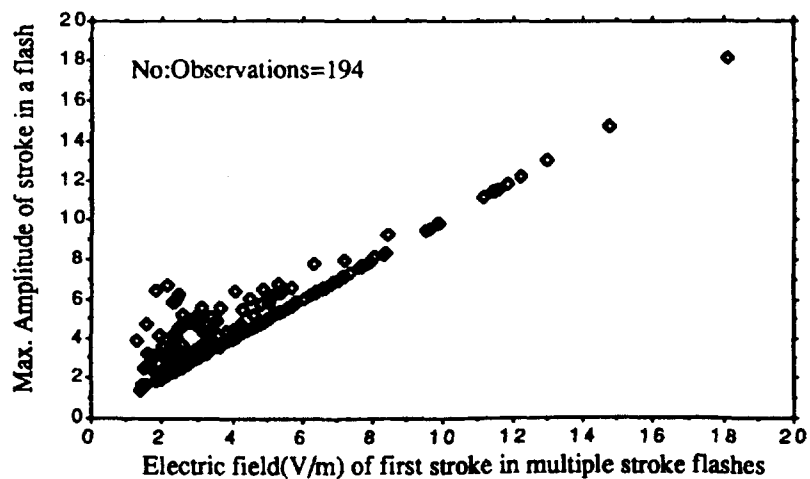


Figure 4: Amplitude ratio of the largest stroke to the first stroke in the same flash

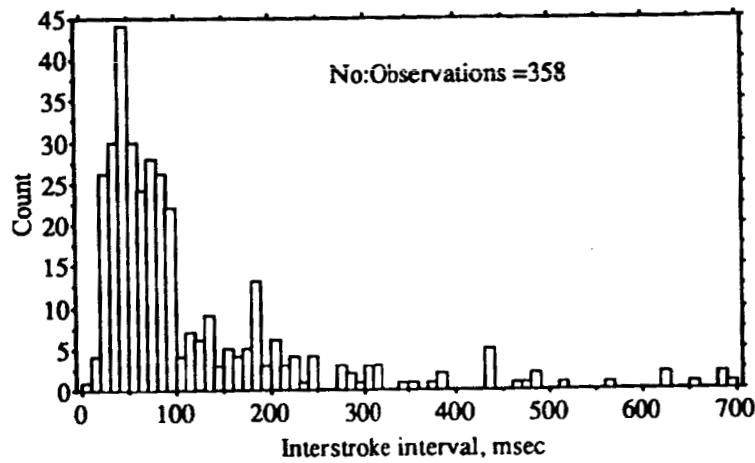


Figure 5: Histogram of subsequent stroke separations in milliseconds

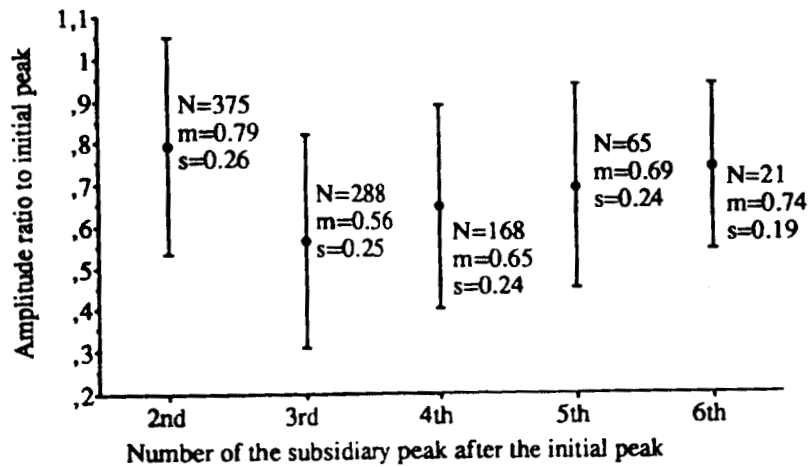


Figure 6: Amplitude ratio of secondary peaks to initial peak

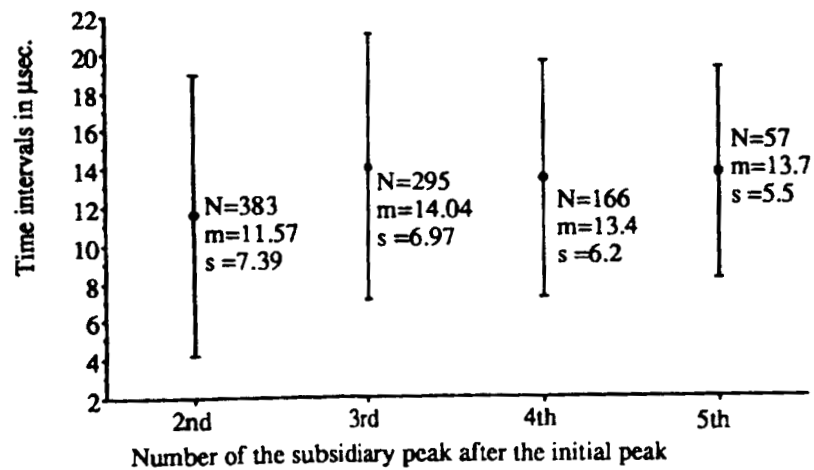


Figure 7: Time separations between subsidiary peaks in μseconds

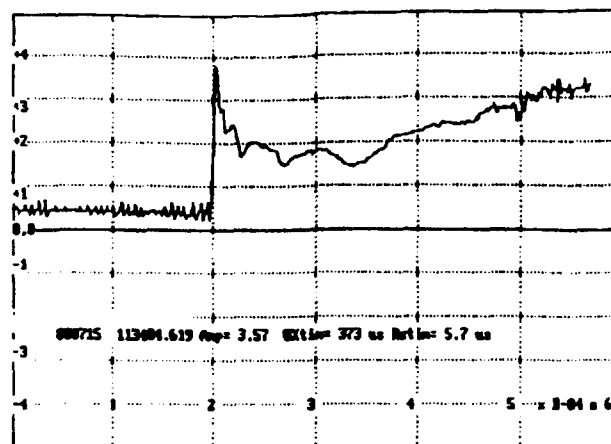
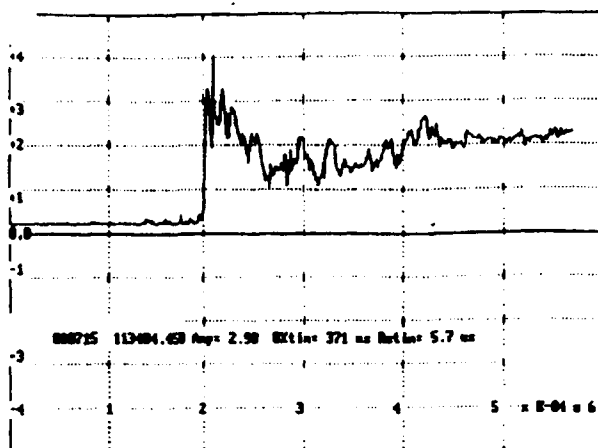


Figure 8a and 8b: The electric field waveforms of the first and subsequent strokes of a close flash within 50 km distance.

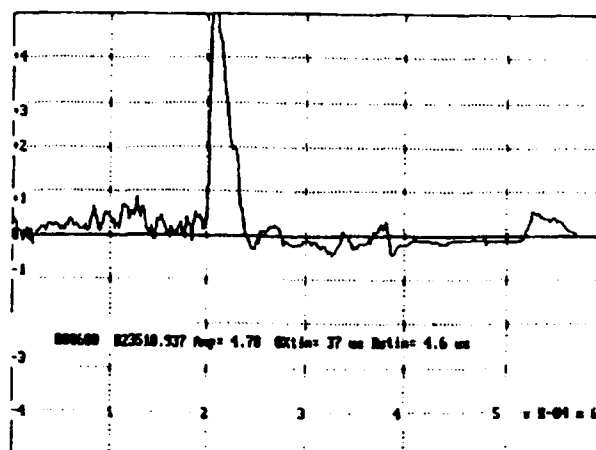
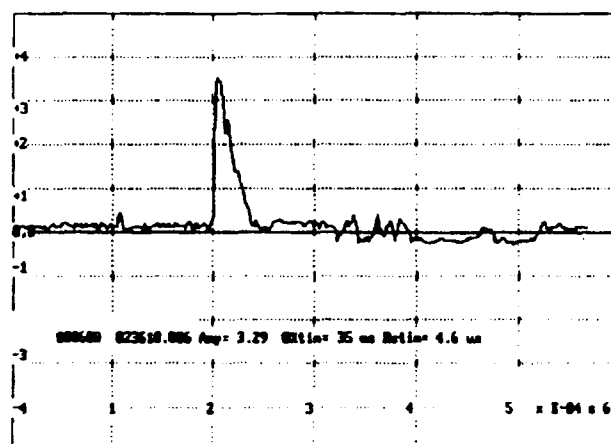
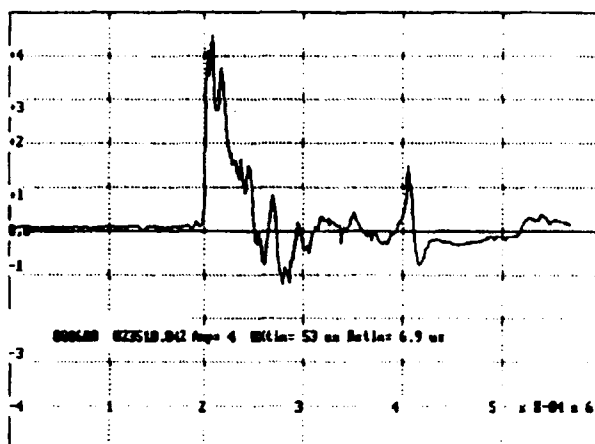


Figure 9a, 9b and 9c: The electric field waveforms of the first and the next two subsequent strokes in a flash at more than 100 km distance.